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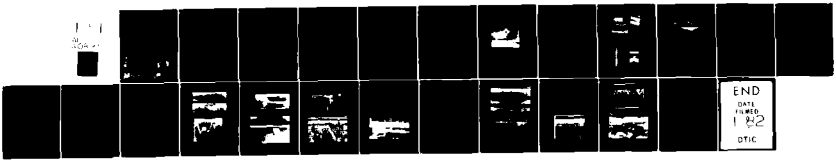

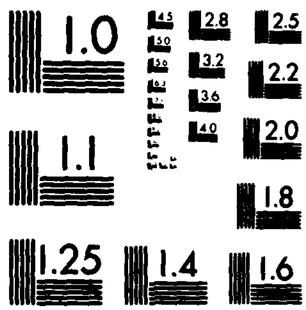

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October 1981

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ELECTROMAGNETIC SUBSURFACE MEASUREMENTS

Arnold M. Dean, Jr.

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In 1974 personnel at the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) began using an impulse radar system to profile accumulations of ice forms. Through field experience, the system has been modified so that it can be effectively used as a profiling system, in a ground or airborne configuration, in certain high-noise environments. The system can penetrate fresh water and media with a high water content. For instance, frazil and brash ice accumulations with approximately 50% water have been profiled to

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20. Abstract (cont'd)

a depth of 25 to 35 ft. As a result of the CRREL modifications, the system has found extensive and varied applications as a low-level remote sensing tool. Applications include profiling ice accumulations (including ice jams), river beds, sheet ice, permafrost, subsurface ice masses, river bank revetments through air-entrained water, snow covers, sea ice, icebergs, and peat bogs. Limited laboratory work has also shown that the impulse radar system may be able to detect oil and gas under sea ice. Selected applications and data are presented. Since it has been used mainly for research, the CRREL system needs further development to make it useful to operational units. Additional development of hardware and software is recommended.

Preface

This report was prepared by Arnold M. Dean, Jr., Electrical Engineer, of the Ice Engineering Research Branch, Experimental Engineering Division, U.S. Army Cold Regions Research and Engineering Laboratory. Major funding for this research was provided by U.S. Army Corps of Engineers Civil Works Project CWIS 31350, Formational Processes of Frazil Ice.

Dr. Steven Arcone and Ronald Atkins of CRREL technically reviewed the manuscript of this report.

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ELECTROMAGNETIC SUBSURFACE MEASUREMENTS

by

Arnold M. Dean, Jr.

INTRODUCTION

In 1974, CRREL purchased an impulse radar system to be used in profiling accumulations of certain ice forms. Geophysical exploration was the major market for the commercially available unit at that time. Through field experience, CRREL personnel have modified the system so that it can be effectively used in an airborne configuration and in certain high-noise environments. An important characteristic of the system is its ability to penetrate fresh water and media with a high water content, in addition to conventional soils profiling. As a result of the CRREL modifications, the system has found extensive application as a low-altitude airborne remote-sensing tool. This report describes the system and a selected number of its applications. It recommends additional developmental work that would make the system useful to operational units.

SYSTEM CHARACTERISTICS

Unlike a conventional radar system, which emits narrow-band pulses whose energy is centered about a particular frequency, the CRREL system emits pulses of energy that have a broad band of frequencies. The energy from the broadband system cannot be focused as well as that from the single-frequency system, but the broadband system exhibits a composite of qualities of the frequencies within its bandwidth. The higher frequencies give better resolution while the lower frequencies have superior penetration capabilities. Depending upon the antenna used, the center of the band may vary from 100 to 600 MHz. The bandwidth varies from about 150 to 200 MHz and the peak radiated power from 2 to 15 W.

The basic components of the CRREL radar system are the power converters, the antenna, the magnetic tape recorder, the graphic recorder and the control unit. Converters are available from the manufacturer to power the system from commercial a.c. and from various d.c. sources. One antenna, whose center frequency is about 300 MHz, is shown in Figure 1. It is attached to the side of a U.S. Coast Guard SAR (search and rescue) helicopter and is used in remote profiling. The radio frequencies (RF) of the system are transmitted and received by the antenna. The antenna is driven repetitively at 50 kHz by pulses varying from 1 to 4 ns in width. The antenna receiver samples the returned signal, converts it to lower (0 to 50-kHz) audio frequencies (AF), and sends it to the control unit. The

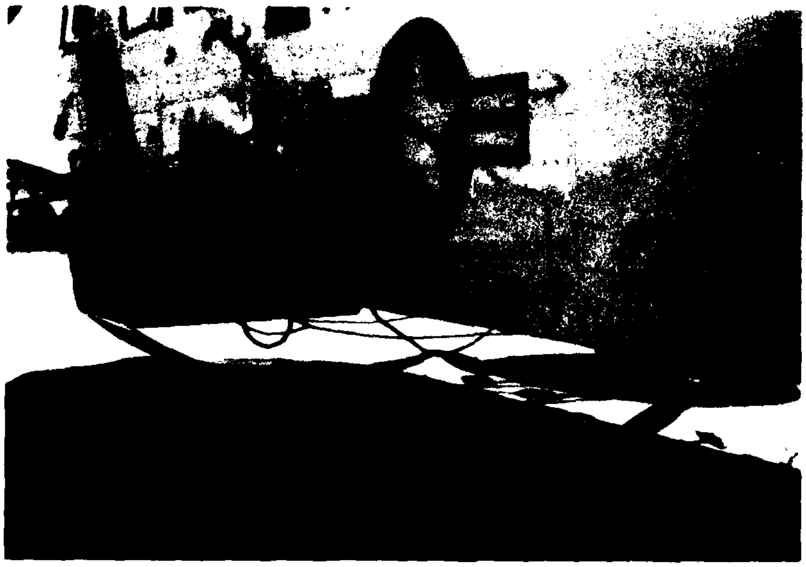

Figure 1. 300-MHz shielded airborne antenna attached to USCG aircraft.

antenna is a resistively loaded "bow tie" dipole and is shielded to minimize rear and side emissions.

The control unit (upper left, Fig. 2) receives the analog signal shown on the left in Figure 3. The wavelets in the signal represent typical returns from an interface where the characteristic impedance of the medium changes. The initial transmitted pulse indicated in the figure is a feed-through of the emitted signal to the receiver. The control unit, which contains an 8-bit microprocessor, generates all voltages required by the system (other than the 24-V d.c. supplied by the power converter), displays the analog signal after various operations in the control unit, provides a programmable gain to the signal, and generates control and timing signals for the system components. The microprocessor, which has an externally programmable read-only memory (PROM), samples, digitizes and Fourier-transforms the input in order to implement a digital filter. The gain and bandwidth of the filter may be changed with the thumbwheel switches shown in the small box to the right of the control unit in Figure 2. The band-

pass filter was empirically designed to take out high-frequency noise and low-frequency echoes from stationary or slowly moving objects (with respect to the antenna). In addition to the filter characteristics, the operator chooses the relationships among gain of the signal with time, sampling rates and recording rates. The control unit also contains a nonbiasing filter which prevents harmonic interference.

A hard copy of the received signals is made on the graphic recorder (foreground, Fig. 2). The graphic recorder provides a 19-in. display on electrosensitive (NDK) recording paper with a dynamic range of 23 dB and presents in excess of 3,000 data points with each sweep. The recorder prints the portion of the signal extending beyond the selected graphic threshold. On the left of Figure 3 are shown the signal from one scan and the threshold, while the printout of several scans is shown on the right in the figure. The third dimension (i.e. horizontal travel, or time) is necessary to interpret the radar data. The graphic recorder may be driven directly from the control unit during data collection, or the magnetically recorded data may be played back through the control unit to the graphic recorder after the data are collected. Speed, intensity, threshold, gain, synchronization, phasing, and scan rate are selected by the operator.

The control unit requires that one of the four channels of the analog tape recorder contain timing pulses. These pulses are put on the channel prior to data collection, controlling the rate at which the data are collected. The entire radar system is then synchronized and driven by the timing channel on the tape recorder. Raw and processed data may be recorded on the magnetic tape in real time and recorded data may be reprocessed during playback.

The physical characteristics of the components of the radar system are listed in Table 1.

A typical data collection configuration is shown in Figure 4. The survey vehicle will contain a power converter, the antenna, the recorder,

Table 1. Physical characteristics of the CRREL impulse radar system.

	Weight kg (lb)	Dimensions, h x w x l (cm)	(in.)
Control unit	11 (24)	18x44x29	(7x18x16)
Graphic recorder	27 (60)	12x82x53	(5x33x21)
Tape recorder	28 (62)	41x48x24	(16x19x10)
Antenna (T/R combined)	36 (80)	34x97x94	(14x38x37)
Airborne antenna (T/R separate)	7.5 (16.5)	27x54x90	(11x22x35)

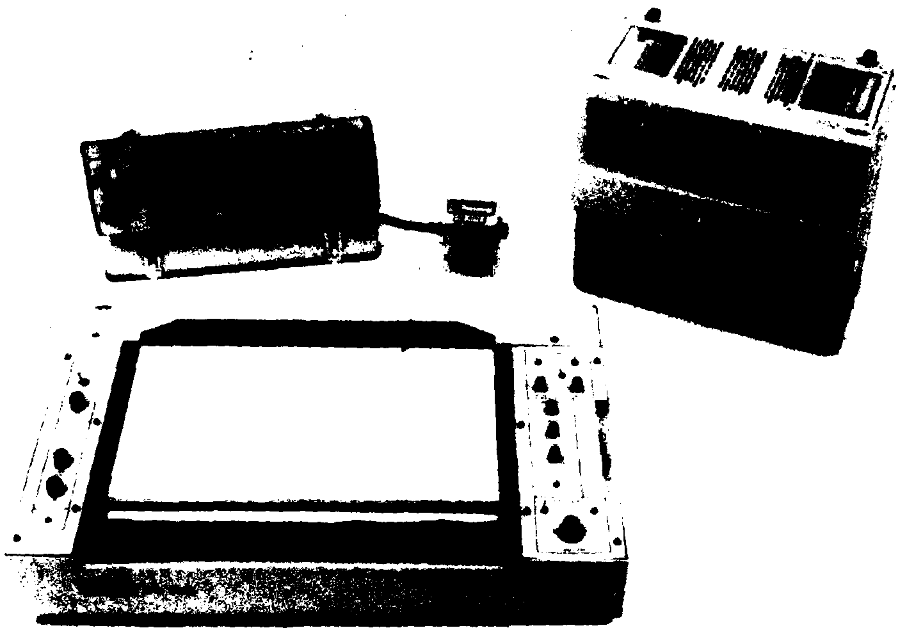

Figure 2. Basic components of impulse radar system. Clockwise from upper left: control unit with microprocessor programming control, magnetic tape recorder, graphic recorder.

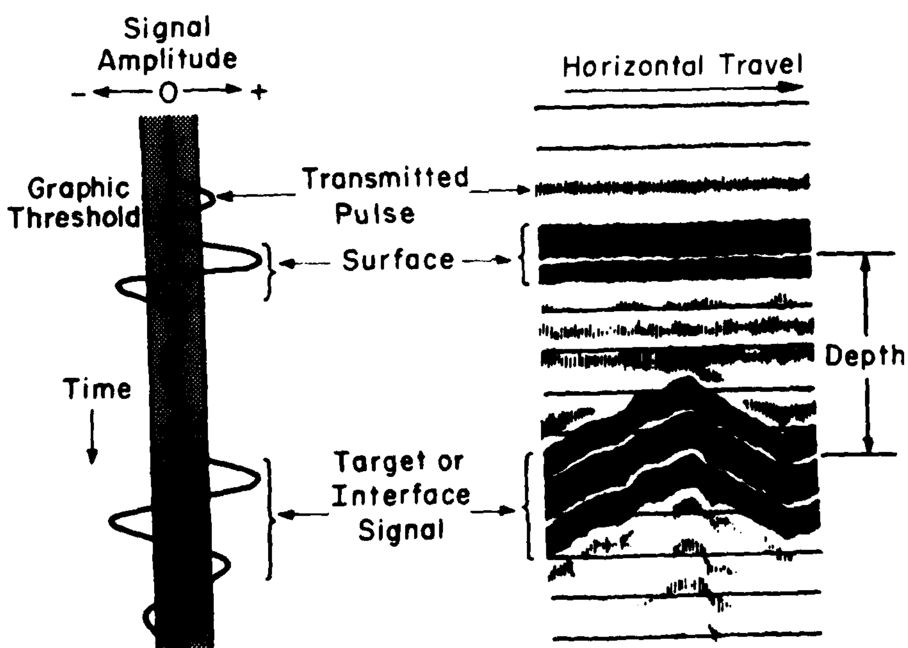

Figure 3. Typical return signal and its graphic analog (composite of several returns).

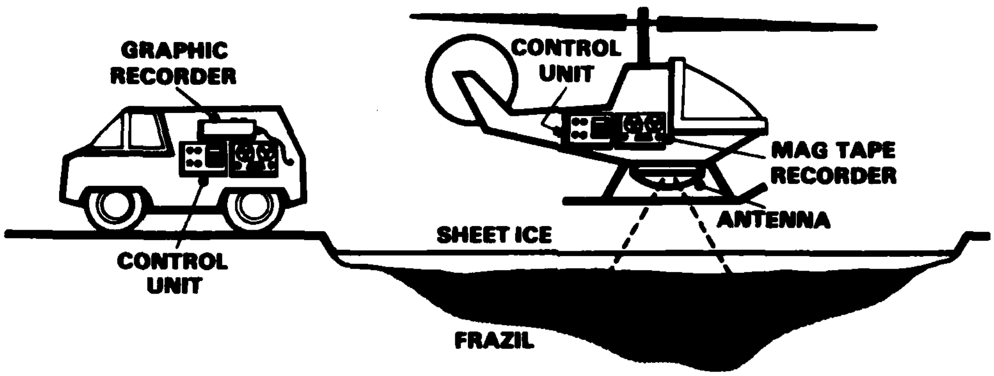

Figure 4. Radar components during airborne data collection.

and the control unit. After the survey, the control unit and survey recorder are transferred to ground-based operation. This transfer is usually made for convenience and availability of power. As explained below, playback to hard copy takes at least eight times longer than the survey period if the data are originally taken and stored on magnetic tape. Furthermore, the tape recorder and graphic recorder are sensitive to prolonged low temperature, and the graphic recorder's power requirement makes a battery/ inverter supply impractical.

Seldom will the graphic recorder be used as the survey recorder, since the scan rate of the system must be reduced to accommodate the graphic recorder's lack of speed. The lower the scan rate, the fewer the samples made per unit length of the survey path. When variation in subsurface geometry is high, the maximum scan rate should be used. At the maximum rate, the interval between samples is 22 cm when the survey vehicle travels at 40 km/hr, or 2.8 cm when the survey speed is 5 km/hr. The selection of scan rate and survey speed is a function of how well the profile must be described.

Although the points in the media which are sampled by the radar are discrete, the scan rate and the coverage of an area by the footprint of the antenna signal provide an effective integrating function. The return, then, can be considered a continuous subsurface profile when vehicle speed and scan rate are properly selected.

With the proper orientation of an unshielded antenna, the field pattern would resemble a toroid whose axis of revolution is transverse to the survey line. With the top and sides of the antenna shielded, for a

first-order approximation of the ground, the antenna pattern would resemble the lower half of the toroid. This results in a somewhat elliptical footprint on the surface, with the major axis of the ellipse along the survey line. If the survey is taken by air at about a 3-m height with the antenna's 3-dB aperture assumed to be 30° to 50°, the minor axis (or transverse footprint dimension) on the surface is about 1.5 to 3.0 m. The shape of the footprint side aids the interpretation by giving a characteristic pattern to reflective subsurface objects. The curve marked "typical" in Figure 5 idealizes a reflective target signature. As the target is approached, the elongated antenna pattern "sees" it well in advance of being over it. The signal reflected back from the target becomes "closer" to the surface as the antenna approaches. The signal is closest to the surface when the antenna is directly over the target. As the antenna moves away from the target, the reverse occurs. When observing the typical signature, one assumes that the target is equally reflective in both dimensions and that the antenna is horizontal. In fact, the orientation of the target may be determined by proper interpretation of the target signature. For example, assume the target is a plate tilted toward the approach direction of the survey. The signature on the upswing of the typical curve in Figure 5 would be strong. As the target is passed over, however, the emitted signal would be reflected away and very little would be returned to the receiver in the antenna. The right half of the typical curve would fade out quickly, revealing the plate orientation.

The lower frequencies in the bandwidth of the broadband impulse radar system give it improved penetration characteristics in comparison with conventional single-frequency radar whose frequencies are at least an order of magnitude higher. Furthermore, the range of frequencies gives the radar the ability to penetrate fresh water or a saturated medium, a characteristic that the higher frequencies cannot enjoy. The dielectric constant and the conductivity of the medium greatly affect the penetration. Ranges for these parameters are found in Table 2.

The propagation velocity v_{pm} of the signal in a low conductivity medium,

$$v_{pm} = c/\sqrt{\varepsilon_r} \tag{1}$$

where c is the velocity of light (3×10^8 m/s $\approx$ 1 ft/ns), and ε_r is the real part of relative dielectric constant of the medium (assuming no dispersion), is seen to be a function of the relative dielectric constant. The depth to a particular target may be determined by the equation

$$d = (c/\sqrt{\varepsilon_r})\ (t/2) \tag{2}$$

$$= v_{pm}\ t/2$$

where d is the depth to the target (or distance between interfaces), and t the measured time on the graphic display.

Note that the time is actually the down-and-back time measured on the graphic recorder and not the actual time of flight through the medium. As an example, refer back to the distance between the surface and interface wavelets in Figure 3. When one measures the time associated with that distance, it is actually the time for the impulse to leave the transmitter, reflect off the interfaces, and return to the receiver. This is the time tabulated in the propagation time column of Table 2, and accounts for the 2 in the denominator of eq 2 (since time of flight is needed in that equation).

The conductivity, dielectric losses, and geometric properties of the medium control the depth of penetration. The higher the conductivity, the more the material will absorb the emitted energy and reduce the penetration. For instance, the radar cannot penetrate sea water. Likewise, if the particles of the medium geometrically scatter the signal, the penetration is reduced.

Table 2. Conductivities, dielectric constants, and propagation velocities of various materials (courtesy of GSSI).

	Approximate conductivity, σ (siemens/m)	Approximate dielectric constant, ε_r	Graphic display propagation time per foot (ns)
Air	0	1	2
Fresh water	10^{-4} to 3×10^{-2}	81	18
Sea water	4 to 5	81 to 88	18-19
Fresh water ice	10^{-4} to 10^{-2}	4	4
Sea water ice	10^{-2} to 10^{-1}	4 to 8	4-6
Ice (glacial)	10^{-6} to 10^{-4}	3.2	3.6
Permafrost	10^{-5} to 10^{-2}	4 to 5	4-5
Snow firn	10^{-5} to 10^{-5}	1.4	2.4
Granite	10^{-9} to 10^{-3}	8	5.6
Sand, dry	10^{-7} to 10^{-3}	4 to 6	4-5
Sand, saturated (fresh water)	10^{-4} to 10^{-2}	30	11
Silt, saturated (fresh water)	10^{-3} to 10^{-2}	10	6.3
Clay, saturated (fresh water)	10^{-1} to 1	8 to 12	6-7
Average "dirt"	10^{-4} to 10^{-2}	16	8

In order to determine the actual propagation of the signal in a medium, ground truth is obtained along the survey path. In most applications at CRREL it has been found that the dielectric constant of the area is reasonably bounded so that an average value may be used. There are exceptions, obviously, where this is not the case. In such instances the depth to a target may be determined in a manner which does not require knowledge of the dielectric constant. Consider the triangle XYZ in Figure 5, and the corresponding times taken from the graphic recorder printout, t_x, t_y and t_z. Now, geometrically,

$$x^2 + y^2 = z^2$$

and

$$y/z = t_y/t_z.$$

Then, substituting,

$$y = x \frac{1}{(t_z/t_y)^2 - 1}$$

or

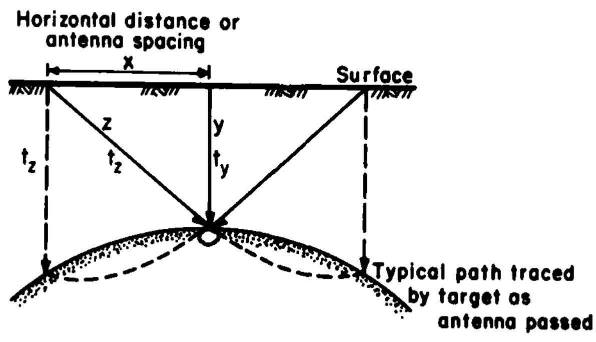

Figure 5. Typical target signature

$$y = kx$$

where k is a constant and a function only of the ratio of velocities along two paths. This relationship and the indirect measurement technique are valid only when the immediate area is homogeneous.

Accuracy in the field is more a function of the consistency of the dielectric constant than of the characteristics of the radar. One is concerned with the system's ability to resolve targets or interfaces which are close together. Looking again at Figure 3, one notes that a target has a characteristic wavelet which is reflected back. This wavelet is represented by the set of three bands in the graphic display. The strength of the reflection determines the "ringing," or the number of bands, while the main frequency component of the signal determines the width of the bands. Practically, the 600-MHz antenna can resolve to a few centimeters, while the 200-MHz antenna can resolve to a few decimeters.

The system is susceptible to noise with frequency components in the passband, which can originate from microwave transmitters, local FM radio stations, and aircraft transmitters. The noise appears to come only through the antenna receiver. In the case of the first two sources, low-level surveys (2 to 3 m off the surface) can reduce the noise level enough so that the data may be interpreted. When the data are taken with the antenna in contact with the surface, a noise problem will usually not exist. Furthermore, it is a simple matter to request that no communication transmissions be made from the survey aircraft during the data collection.

The field-worthiness of the system has been well proven over the last six years by CRREL personnel. It has been carried and shipped from New Orleans to Alaska and has operated behind and in vehicles on the ground, in the water, and in the air. It appears to be the first commercially available profiling system of its kind which operates in the field and in high-water-content media. The graphic and tape recorders do not function reliably below 0°C, but no upper temperature restrictions have been encountered in the field. The system is reasonably splash-resistant and can function in high humidity conditions.

Whereas interpretation of simple strata and targets is straightforward, the interpretation of a complex profile requires extensive experience. Since nature seldom provides simple geometry, the utility of the system for profiling complex conditions is limited by the availability of highly trained personnel.

SYSTEM APPLICATIONS

As with any remote sensing tool, the impulse radar system provides a significant advantage to manual profiling in large or hazardous areas.

When a reliable and continuous record of the variations in a locally homogeneous medium is required, the system is far superior to periodic sampling. The CRREL system has a record of use on the surface, in the water, and in the air. A selection of the data from field work is described and shown in this section as indicative of the system utility. A typical return from a multilayered dry medium (river bottom and terrace deposits) is shown in Figure 6. This reproduction, taken by the system manufacturer several years ago, is overlaid with multiple reflections (indicated by horizontal bands running the length of the graphic). In this case the reflections are not severe enough to prohibit interpretation. The strong returns (heavy lines) on the top of both profiles represent a combination of the feed-through pulse and the ground surface. Below the surface there are combinations of targets and reflections (echoes), as layers are distinguished. Note that the penetration of the signal (the strength of the returns) is drastically reduced upon entering the varved clay strata on the top scan. This is probably due to the high conductivity of clay. In comparison, several strata are observed in the lower scan.

Interest in the location and mapping of potential fuel sources led the manufacturer to test the system in a peat bog. The results of a ground profile are shown in Figure 7. The profile of the deposit is easily determined, since the lower bound is typically clayey and quite reflective. The sets of vertical dashed lines are electronically induced benchmarks. Incidentally, Figure 7 illustrates why movement or time is needed for the interpretation of the data. One notes several sets of horizontal lines of various densities. One set is at the beginning of the scan; a second set is just before the first dark vertical benchmark. These line sets indicate that the survey movement was stopped for a short period. The result is a record of the reflections at the resting point. As is seen, it is impossible to discern valid target returns from echoes until the natural variation in targets or surfaces is observed during the traverse.

Figure 8 shows the data from a profile taken through the bottom of a wooden boat. The lake bed, subbottom material and strata, and large rocks are identifiable. Note the classic target signature of the item seen just to the right of the arrowhead pointing to the lake bottom. The trails of two and three bands from this target extend to the bottom of the graphic. Again, the straight vertical lines are benchmarks intentionally placed on the data.

One technique used by the Army for cold regions mobility is construction of ice bridges. A typical bridge is shown in Figure 9. When time, hydraulic conditions, and/or temperature are critical, a continuous profile of the bridge is needed (Fig. 10). Sheet ice thickness can be continuously measured, as can the location of the stream channels, gravel bars, and other ice forms.

As an interesting aside to surface measurements with the radar, the manufacturer also profiled a railroad bed in an attempt to identify de-

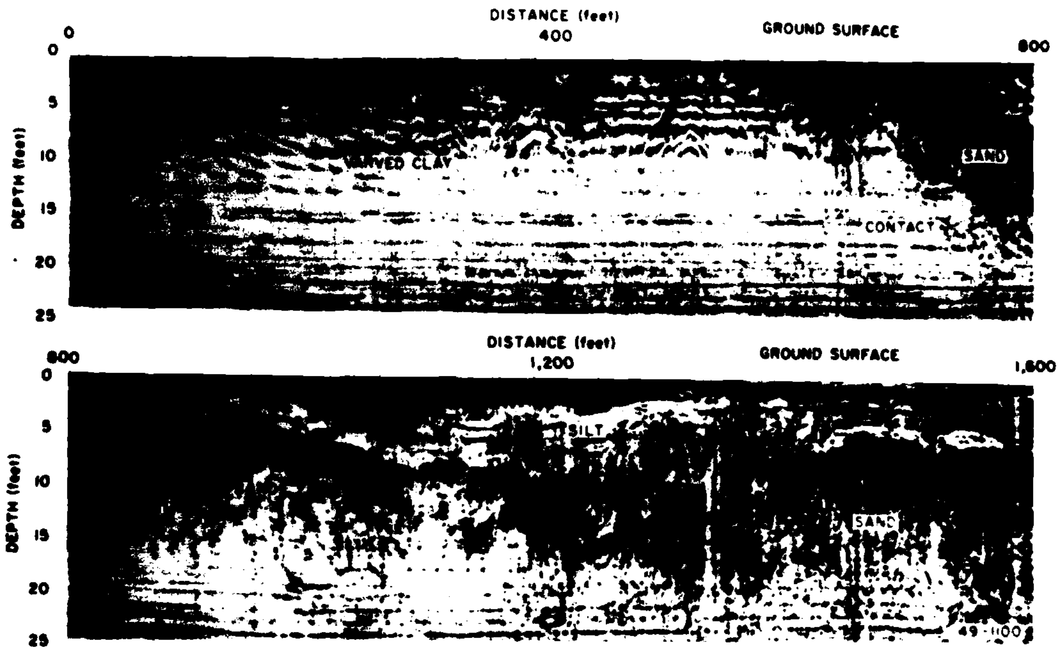

Figure 6. Lake bottom and river terrace deposits (courtesy of GSSI).

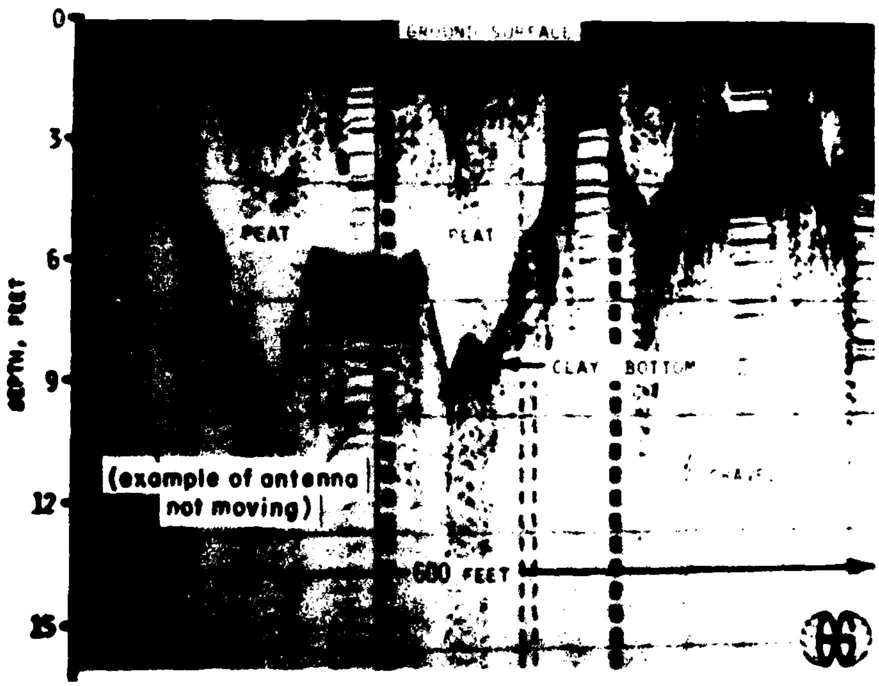

Figure 7. Radar depth profile of peat in a cleared forest
(courtesy of GSSI).

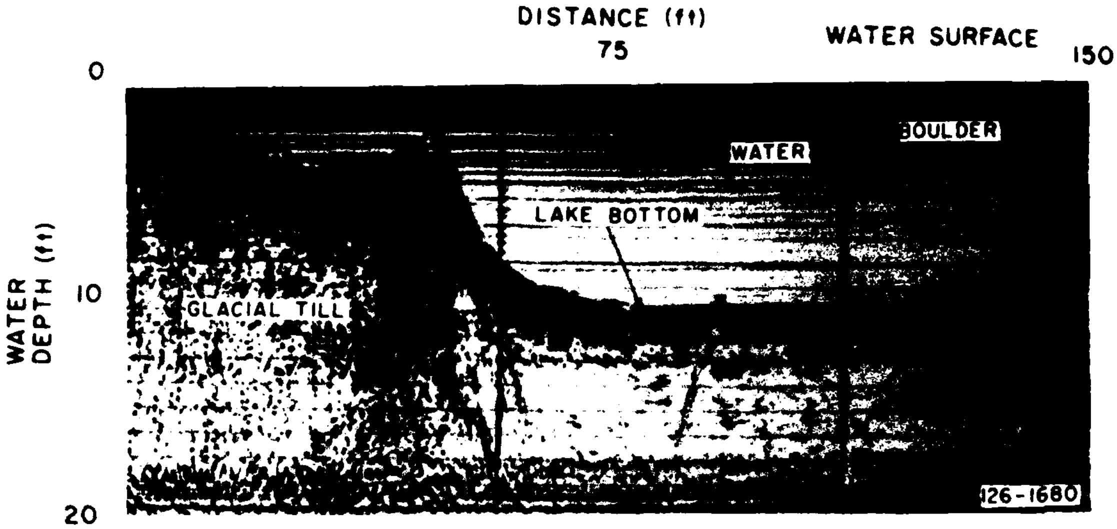

Figure 8. Lake bottom profile (courtesy of GSSI).

Figure 9. View of ice bridge looking across the Tanana River near Fairbanks, Alaska.

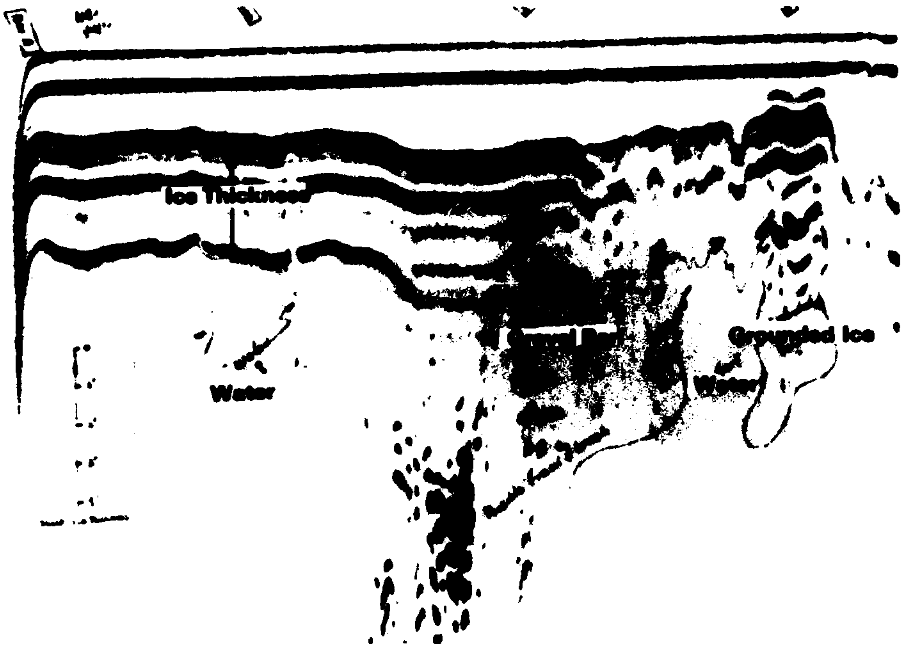

Figure 10. Radar profile of ice bridge shown in Figure 9.

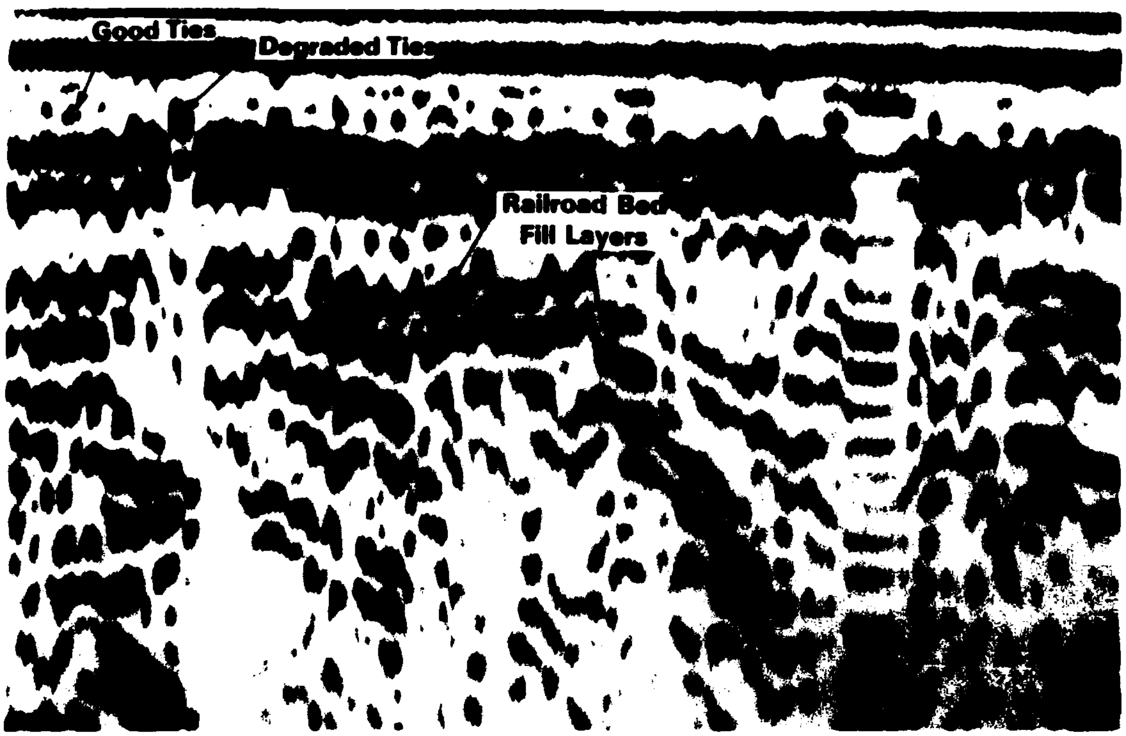

Figure 11. Radar investigations of railroad ties and fill layers (courtesy of GSSI).

graded ties. Figure 11 shows that the degraded ties exhibit a higher dielectric constant, making them and the first fill layer appear closer to the surface (refer to eqs 1 and 2).

A potential application of the impulse radar system is profiling in air-entrained water, a classic weak point for sonar systems. Radar has no trouble penetrating air-entrained water, but as the conductivity of the medium increases, the penetration of the radar is significantly reduced. On one occasion the impulse radar system was tested in the white water below a low sill structure on the lower Mississippi River. It was hoped that stone movement near the revetment could be monitored under dynamic conditions. Prior to the test the conductivity of the water was typically in a range that made this application reasonable, but the system was able to follow the revetment down only to about 5 m. Conductivity measurements were not available, but high values were suspected since structure grouting and maintenance work were in progress (Fig. 12). Similar profiling in air-entrained water below hydroelectric plants in New England has easily penetrated down to 10 m.

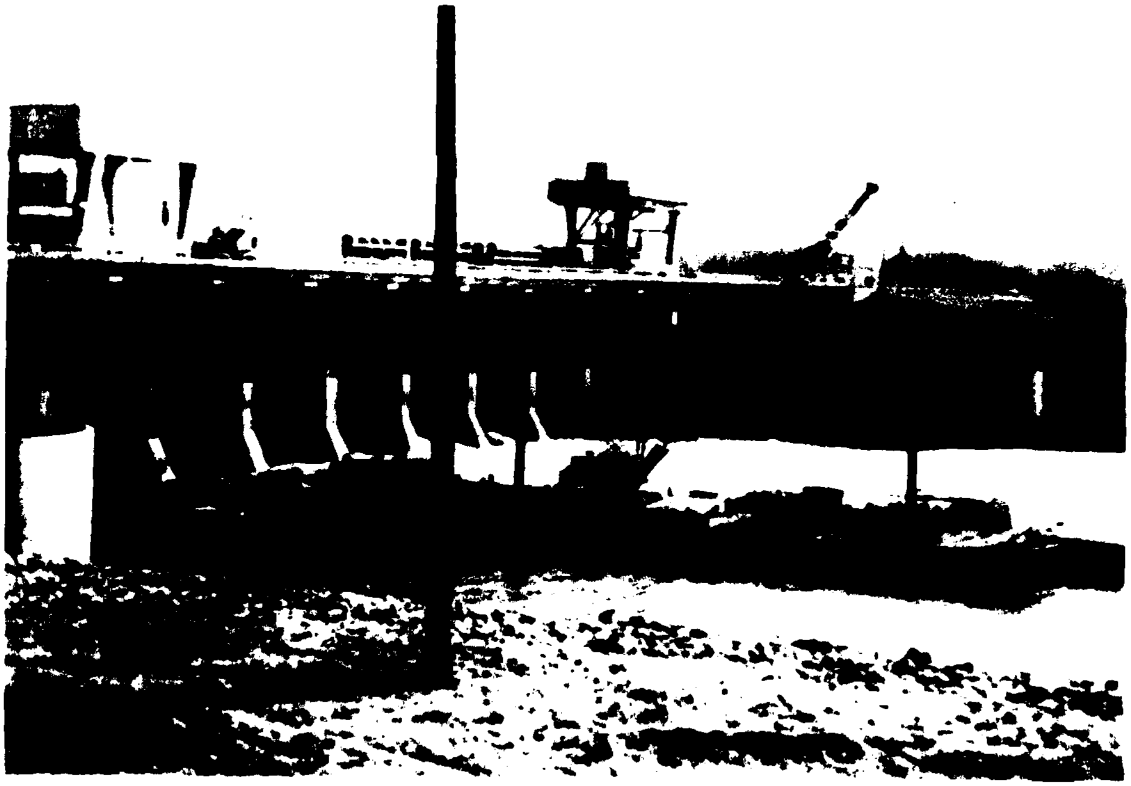

Figure 12. Tailrace of the low sill structure on the Mississippi River where radar was tested in air-entrained water.

The majority of work by the Ice Engineering Research Branch at CRREL with the impulse radar has been in the airborne configuration. This includes mounting the antenna under helicopters and suspensions from the bows of icebreakers and from bridges. Figures 13-15 provide examples of data acquired with the radar mounted on a USCG SAR helicopter and the resulting interpretation. The profile is a transverse section of the river where ice accumulation due to ship traffic, hydraulic conditions, and weather had created an impasse to unaided vessels. The bands across the profile in Figure 13 are due to reflections from the helicopter and make interpretation difficult, if not impossible. Figure 14 shows the same cross section after the data had been processed by the internal computer, and Figure 15 adds a vertical and horizontal scale to the interpretation sketch of the previous figure. Information obtained from such cross sections was previously unavailable since the ice rubble and surface instability created an inaccessible area. Ground truth measurements agreed to within a few percent with the radar interpretation in this work.

By suspending the antenna on a boom in front of an instrumented USCG icebreaker, researchers are able to continuously correlate ice thickness with the ship's power requirement under various operating conditions. Figures 16 and 17 show the same section of raw and processed icebreaker data, respectively. The classic target signatures can be identified from the processed data, whereas the raw data are uninterpretable.

The data acquired from the icebreaker are similar to those which represent the thickness of ice striking bridge piers (Fig. 18). In this case, the antenna was suspended from the bridge deck to determine the feasibility of the data collection technique. The approach was successful, and the radar is now being used in conjunction with instrumented bridge piers to correlate the forces exerted on the piers during ice runs and the thickness of the attacking ice. Since the ice cover is made up of discrete pieces of various sizes (rubble), a ground truth measurement is made in this application by averaging several point measurements in an area. The agreement of the radar in these areas of rubble was found to be between 3% and 5%.

CONCLUSIONS AND RECOMMENDATIONS

The CRREL broadband impulse radar system has been proven during field use over the last several years for a variety of applications. The system is very fieldworthy and offers distinct advantages over conventional data collection techniques. The radar can be used in an airborne configuration to remotely survey large and inaccessible areas and can provide a continuous profile along the survey path. Because of its broadband signal content, it has system accuracy in decimeters and the ability to penetrate 5 to 15 m of water (depending upon conductivity).

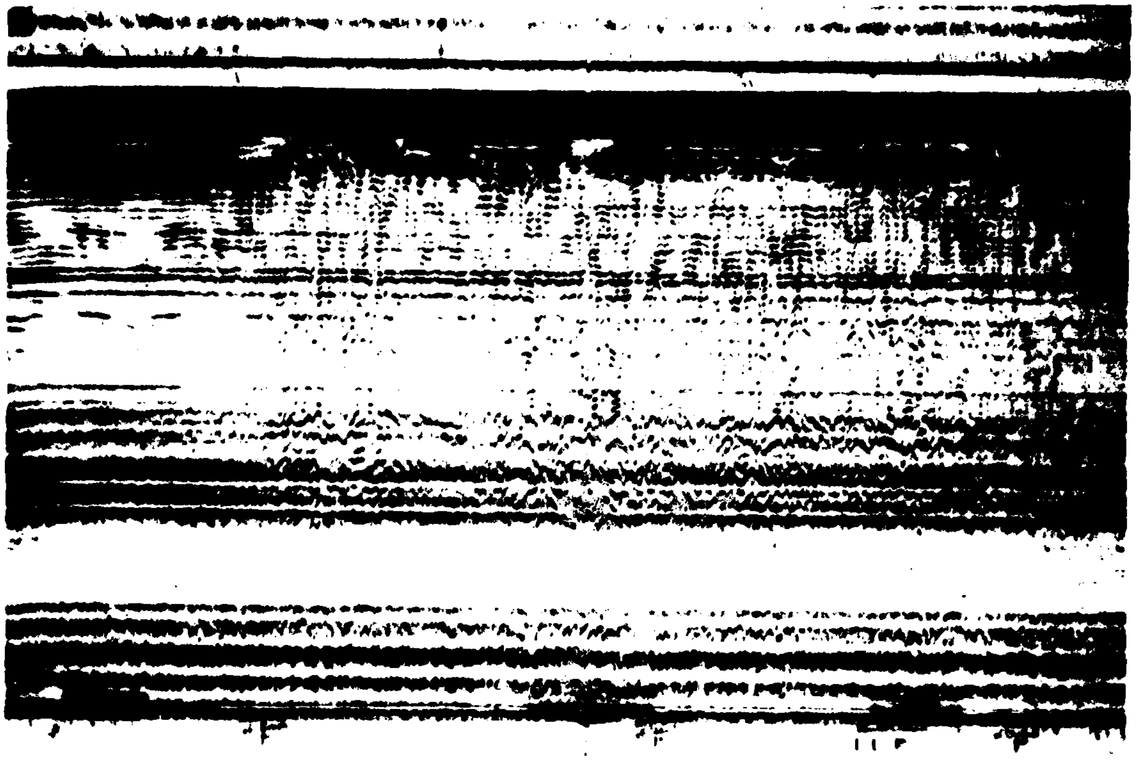

Figure 13. Cross section of ice accumulation due to ship traffic on the St. Marys River near Sault Ste. Marie, Michigan; raw data.

Figure 14. Cross section of ice accumulation due to ship traffic on the St. Marys River near Sault Ste. Marie, Michigan; processed data.

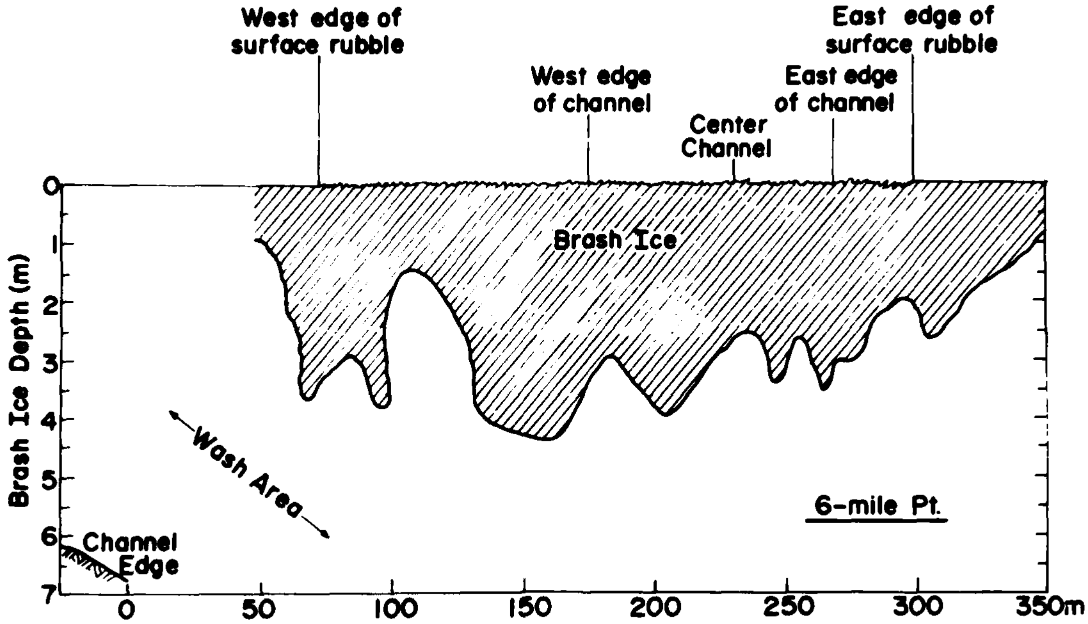

Figure 15. Cross section of ice accumulation due to ship traffic on the St. Marys River near Sault Ste. Marie, Michigan; artist's sketch of interpreted data.

Figure 16. Radar image of brash ice thickness taken from the bow of USCG icebreaker; raw data.

Figure 17. Radar image of brash ice thickness taken from the bow of USCG icebreaker; processed data.

Figure 18. Ice run attacking a bridge pier on the Athabasca River at Ft. McMurray, Alberta, Canada.

The system needs further development to make it useful to operational units. At present, highly skilled and experienced personnel must be used for interpretation. Additional hardware and software development could greatly facilitate interpretation and reduce the level of skills required by the operators. Some areas in which work is needed include the implementation of a faster microprocessor with more sophisticated data manipulation in real time, the development of a "scroll"-type interactive CRT display for real-time two-dimensional data manipulation, and the development of an antenna with a more focused and defined pattern.

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